RESEARCH DEPARTMENT

A SURVEY OF FACTORS LIMITING THE PERFORMANCE OF MAGNETIC RECORDING SYSTEMS

Report No. C-091

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ERRATA

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Page 7, paragraph (b) - Sensitivity factor, $S_b/A = 0{\cdot}29$ *should read,*

Sensitivity factor, $S_b/S = 0{\cdot}29$

paragraph (c) - Sensitivity factor, $S_b/A = 0{\cdot}065$ *should read,*

Sensitivity factor, $S_b/S = 0{\cdot}065$

Page 26 - The first equation on this page should be numbered (29) *instead of* (31)

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1. INTRODUCTION.

Magnetic recording is now firmly established as a system of storing information, using the term in its broadest sense, in the scientific, artistic and commercial fields. The increasing extent to which it is used in a wide variety of applications is, of course, largely due to the inherent convenience of the method. In practice the information to be stored is transformed into electrical signals which are fed to a magnetic recording head. This head effects equivalent changes in the magnetisation along the length of a moving magnetic tape, or around a rotating magnetic drum or disk, representative of the electrical signals fed into it. When reproducing at any desired time later, the magnetised medium is driven at the same speed past a reproducing head. The lines of magnetic flux from the surface of the moving medium then induce e.m.f.s in the head which depend on the changes of magnetisation and, hence, the original signals which created them. These e.m.f.s may be amplified and used or displayed in any desired manner. In this system, it must be noted, the medium is ready for reproduction without any processing and, under good conditions, the record is available for many hundreds of reproductions with little deterioration. Moreover, when the particular information recorded is no longer required the medium may be magnetically "erased" so that it is available, unimpaired, for further recording. When in the magnetic tape form the recording is also easily edited, i.e. pieces may be erased or cut out or spliced into a long length of tape and a long record may be made up of shorter lengths from a variety of recordings. Many types of apparatus exist with which a recording of this sort may be made, the particular design depending on the application for which the apparatus is intended and the information storage capacity required. In the recording of sound signals for scientific or artistic purposes, for example, the equipment may be static and provide medium length recording (e.g. 40 minutes per reel at 15 in./sec tape speed) of the highest fidelity. Machines of this type are used in the broadcasting and sound recording industries for the recording of music and speech. In a continuous-recording application static installations of less high fidelity, but using much lower tape speeds, are used at aerodromes for the recording of ground-to-air and air-to-ground conversations or control instructions. Equipment may also be fashioned in an extremely light and portable form to meet such applications as interview or dictation recording where lower recording speeds are desirable and lower quality acceptable. In the scientific field the system may be employed, usually with high recording speeds, as a delay device or for storing metering information or mathematical information in coded form. In these applications the recording medium may still be a tape or it may be a rotating drum or disk, depending on the subsequent speed of access required to the information.

The above applications involve a wide range of signal frequencies and, to some extent, such design factors as tape or drum speed and magnetic head constants may be chosen so that the magnetic system records and reproduces the information efficiently. Development has not, however, yet reached the stage when the system may be exploited to the full in all possible applications and the most important factors which limit its wider use arise from considerations of frequency response and recording speed. These are fundamentally related, for when an electrical signal is recorded a "magnetic waveform" is created in the medium representing the changes of amplitude of the signal with time. Here there is, therefore, the common concept of "wavelength" in the medium as the quotient of recording speed and frequency. It will appear in the course of the discussion which follows that many limitations of frequency response are, in fact, due to wavelength effects, i.e. to the inability of a particular design of equipment effectively to record or reproduce various wavelengths or wavelength ranges. The two main difficulties of this type arise in dealing with either very short or very long wavelengths. One of these may, of course, be avoided by the designer if he has a choice of recording speed but this is not always the case, especially when information storage capacity must be considered. Moreover, in wide frequency-band applications the speed requirements for the effective recording and reproduction of short and long wavelengths are often opposing requirements and some compromise has, therefore, to be made.

In a recent paper[1] Selsted and Snyder have discussed some of the limitations of existing magnetic recording techniques and the influence of the magnetic medium upon them. It is the purpose of the present article to examine such elements as heads, recording media and tape transport systems, which determine the frequency and other characteristics of the magnetic recording system, rather more closely and so to indicate the difficulties and requirements in various types of application. The factors will be considered in the context of the recording and reproducing processes and with reference to frequency effects (i.e. those depending fundamentally only on signal frequency) and wavelength effects (i.e. those depending fundamentally on recorded wavelength). Frequency and wavelength effects may exist independently or together depending on the frequency range and recording speed in any particular application. It should be assumed that the discussion relates to a tape system, unless otherwise stated, although most of the effects described will also be present, in a more or less exaggerated form, when recording on magnetic drums or disks.

2. FUNDAMENTAL PROPERTIES OF MAGNETIC RECORDING.

2.1. Basic Description.

A diagrammatic representation of a tape recording and reproducing system is shown in Fig. 1(a), and a more detailed view of a head is shown in Fig. 1(b). Recording and reproducing heads are usually of similar construction, consisting of a toroidally wound magnetic core of high permeability containing a narrow gap at the point where the tape is brought into contact with the head. During recording, the signal current I is fed to the coil of the recording head and recording takes place by virtue of the leakage field from the gap magnetising the moving tape along its length in a pattern corresponding to the changes in time of the signal current. On reproduction the flux from the magnetised tape is persuaded by the presence of the gap in the reproducing head to pass round the core and induce an e.m.f. E in the coil.

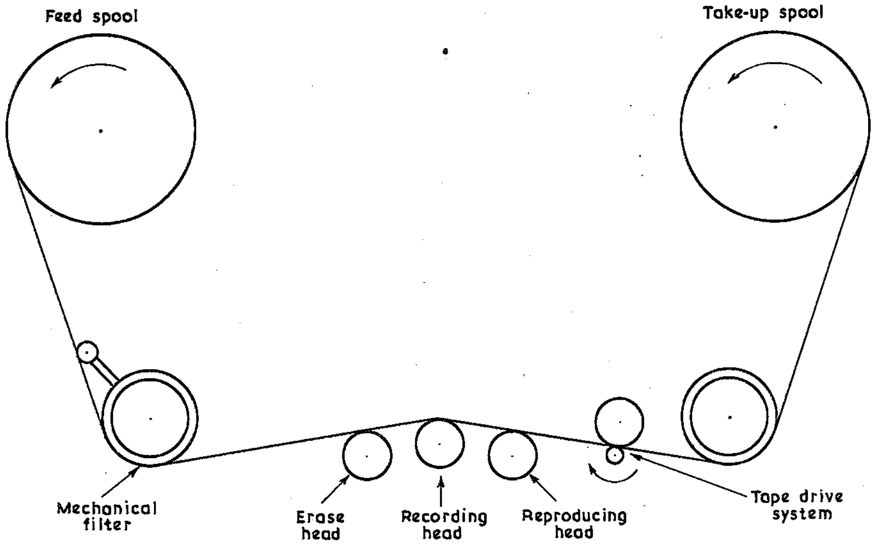

Fig. 1(a) - Conventional layout of magnetic tape recorder

In examining the performance of such systems, the relations between I, E and the magnetic state of the tape, corresponding to various recording signal frequencies (or various recorded signal wavelengths) are of paramount importance. In the next section, the basic nature of these relations is established by an analysis of the behaviour of an idealised, loss-free magnetic recording system.

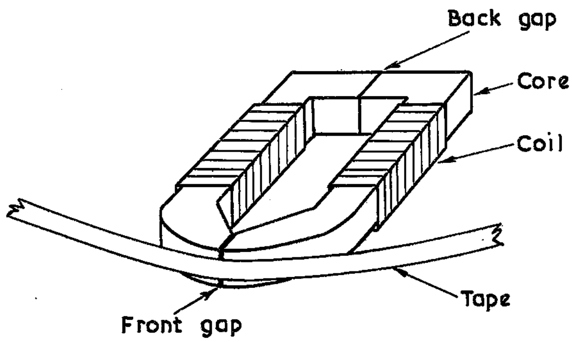

Fig. 1(b) - Structure of conventional magnetic head

2.2. The Idealised System.

Let the recording head be fed with a signal current I varying sinusoidally with time at a frequency f. Then, if the core is of finite permeability, the peak value of the field strength created within the gap is given by

$$\hat{H}_x = (4\pi N'/b')\hat{I} \tag{1}$$

where b' is the length of the gap and N' the number of turns on the coil. It will be assumed that this field strength also exists just above the gap, where the tape is moved across the head at a constant speed v. Provided the transit time b'/v of the tape over the gap is small compared with $1/f$, equation (1) then represents the strength of a recording field which remains substantially unidirectional and single-valued as a given element of tape traverses the gap. Assuming, further, that the characteristic relating the remanent intensity of magnetisation and the field applied to the magnetic material coated on the tape is linearised by some means it is possible to write

$$\hat{J}_x = \eta \hat{H}_x \tag{2}$$

for the intensity of magnetisation in an element of tape after it has left the gap, where η may be termed the "tape sensitivity". Bearing in mind the time variation of the recording field it is clear that the magnetisation will be sinusoidally distributed along the length of the tape and can be written in the form $J_x = \hat{J}_x \sin (2\pi x/\lambda)$ where λ, the wavelength of the distribution, is equal to v/f, and from (1) and (2)

$$\hat{J}_x = (4\pi N'\eta/b')\hat{I} \tag{3}$$

It is now firmly established practice to define the strength of a recorded signal in terms of "surface induction", B_y, the mean magnetic induction normal to the surface of the tape in free space. With the above distribution of magnetisation, it can be shown that the surface induction is of the form $B_y = -B_y \cos (2\pi x/\lambda)$ and if, as will be assumed in this section, the tape thickness c is very small and the tape width w is **very large** compared with λ, $\hat{B}_y$ is given closely by [2]

$$\hat{B}_y = (4\pi^2 c/\lambda)\hat{J}_x \tag{4}$$

provided the permeability of the tape is not much greater than unity. Thus from (3) and (4), the "recording response" of the ideal system is given by

$$\alpha_i = \hat{B}_y/\hat{I} = 16\pi^3 N'\eta c/b'\lambda \tag{5}$$

Thus, the recording response of the ideal system is inversely proportional to wavelength or rises at 6 dB/octave with signal frequency.

To reproduce the signal, the tape is passed at the same speed, v, over a similar head to that used for recording, and a sinusoidally varying flux of the form $\phi = \hat{\phi} \sin 2\pi f t$ is created in the core if this is of negligible reluctance compared with that of the gap b. Peak flux will occur when a half-wavelength of tape bridges the gap in such a way that the flux entering each pole-piece is additive. Provided the length of the pole-pieces is sufficiently great and $b \ll \lambda$, the peak value of flux is, in fact, equal to the flux emanating from the half-wavelength of tape, so that, integrating B_y between appropriate limits,

$$\hat{\phi} = w\lambda\hat{B}_y/\pi \tag{6}$$

The varying flux induces in a coil of N turns wound on the head an e.m.f. E of peak value given by

$$\hat{E} = 2\pi f N\hat{\phi} = (2\pi N v/\lambda)\hat{\phi} \tag{7}$$

Thus, from (6) and (7), the "reproducing response" of the ideal system is given by

$$\beta_i = \hat{E}/\hat{B}_y = 2Nvw \tag{8}$$

which is, therefore, independent of wavelength or signal frequency.

The "overall response" is equal to the product of the recording and reproducing responses and, therefore, should be proportional to frequency in the ideal case. This fact necessitates the introduction of an electrical integrating network into the system when, as is normally the case, the overall response is required to be independent of frequency.

2.3. The use of H.F. Bias.

It is tacitly assumed in the simple analysis given above that the relation between the magnetisation of the recording medium and magnetising field strength is linear. The condition is approximately fulfilled, however, only over a middle range of unidirectional field strength. Below this range the remanent intensity of magnetisation tends to be proportional to the square of the applied field strength and above this range it changes little with field strength as saturation is approached.

The approximately linear portion can be utilised in recording if an appropriate value of "d.c. bias" is fed to the recording head together with the signal current. An approximation to the desired linear characteristic then results over a limited range of alternating signal amplitudes. This method was frequently used in the past and is still found in special applications. It has, however, the undesirable property of greatly increasing the basic noise level of the system.

A method of avoiding this last mentioned difficulty and of obtaining a far better linearity of response over a greater range of signal amplitudes, is to replace the d.c. by an a.c. current of similar peak magnitude and of frequency in excess of (preferably many times greater than) the highest signal frequency. No detailed explanation of the process of h.f. biasing will be attempted here, but a comment on the implication of certain of its properties will be of value in discussing various phenomena in later sections of the paper. Westmijze[3] has pointed out that the use of h.f. bias in the recording process is analogous to the method of anhysteresic magnetisation discussed by Steinhaus and Gumlich[4]. In this method a linear and anhysteresic relation between remanent intensity of magnetisation and unidirectional field strength applied to a specimen is obtained by superimposing on each value of unidirectional field an alternating field of high amplitude and then gradually reducing this amplitude to zero. The maximum amplitude of the alternating field is found to be unimportant, provided it is greater than a certain value, and this is explained by making the following assumption: the final magnetic state of the specimen depends solely upon the instantaneous value of the unidirectional field when the alternating field has been reduced to a certain critical value.

The similarity of this method and the use of h.f. bias in the recording head is obvious if, for example, the longitudinal field distribution of the recording head is considered. This is such that the field strength is a maximum at the centre of the gap and decreases smoothly to zero on either side of it. Thus each element of moving tape is subjected to a maximum h.f. bias field strength at the centre of the recording head gap and to a gradually decreasing value of bias field as it leaves the gap.

In magnetic recording, however, it is observed that the recorded level falls, instead of remaining constant, as the h.f. bias current in the head is increased beyond a certain value. It must be remembered, however, that in the conventional recording head the instantaneous strength of the signal field, as well as that of the bias field, falls to zero as an element of tape leaves the precincts of the recording head gap. Thus when the bias current is excessive, the critical h.f. bias field strength, h_c, may be situated well beyond the trailing edge of the recording gap where the instantaneous signal field is below its value within the gap, and the recorded level will correspond to this lower value of signal field.

An assumption made in the discussion of the ideal system is that the recording field is single-valued. The concept of a critical bias value implies that this assumption is also valid in the practical case since, using h.f. bias, the only effective signal field is that existing at the point where the critical bias field is located. If no h.f. bias is used, or the value of h.f. current fed to the recording head is too small, the recording field is no longer single-valued particularly when the gaplength is large compared with the wavelength. Under these conditions the magnetisation of an element of tape depends not only upon the value of signal field at the critical point near the trailing edge of the gap, but upon the whole of its "magnetic history" in traversing the gap[5]. As discussed later this can lead to effects of great complication requiring a quite separate explanation.

3. RESPONSE AS A FUNCTION OF WAVELENGTH.

3.1. Factors Governing the Reproducing Response.

3.1.1. Gaplength.

In deducing the reproducing response of the ideal system given by (8) it was assumed that the gaplength of the reproducing head was infinitesimal. If a finite gaplength is considered it has been shown[6,7,3] that the response is approximately given by

$$\hat{E}/\hat{B}_y = 2 N v w (\lambda/\pi b) \sin (\pi b/\lambda) \tag{9}$$

which reduces to (8) provided the wavelength is sufficiently long for the condition $\sin (\pi b/\lambda) \approx \pi b/\lambda$ to hold. At shorter wavelengths, however, the response falls until, when $b = \lambda$, it should theoretically be equal to zero. Beyond this point the response rises, reversed in phase, to a maximum when $b = 3\lambda/2$, then falls to zero again when $b = 2\lambda$ and so on. In practice the equalisation of such a characteristic beyond the first extinction point is not feasible and the gaplength must be chosen so that b is appreciably less than the shortest wavelength of interest. Over this limited range (9) may be replaced by a more accurate expression, established both theoretically[8,3] and empirically[7],

$$\hat{E}/\hat{B}_y = 2 N v w (\lambda/\pi b) \sin (\pi b_e/\lambda) \tag{10}$$

where b_e, the "effective gaplength", is equal to the wavelength at which the first extinction is found to occur and is approximately given by $b_e = 1{\cdot}15b$. Taking this correction into account it appears that a "gaploss" of 6 dB occurs when $b = 0{\cdot}58\lambda$ and the precision required in the manufacture of heads for short wavelength work may be appreciated by noting that the gaplength required to lose no more than this amount in reproducing, say, 15 kc/s at 15 in./sec, 250 kc/s at 100 in./sec, or 3 Mc/s at 200 in./sec, are, respectively, 0·53, 0·21 and 0·035 mil.

Both the above expressions for the reproducing response assume that all the reluctance of the head is contained in the gap. In practice, however, the core may have appreciable reluctance. Moreover, for ease of construction and in order to obtain a narrow, well-defined gap at the front, a head core is usually manufactured in two halves, which are afterwards clamped or stuck together, so that a significant gap

(shown also in Fig. 1(b)) may exist in the rear of the head. Under these conditions the reproducing response is obtained by multiplying (10) by the ratio of the front gap reluctance S_b to the total reluctance S of the head, i.e. by the factor

$$\frac{S_b}{S} = \frac{b/A_b}{b/A_b + l/\mu A + a/A} \tag{11}$$

where a is the length of the rear gap, A_b is the area of the front gap, A the area of the core and rear gap and l the length of the core of permeability μ. This factor determines the proportion of the tape flux taking the useful path linking the head coil to that taking the unwanted path across the front gap.

It is evident from these considerations that the length of the front gap of a reproducing head must be chosen with two conflicting requirements in mind: the gap must be small enough to resolve the shortest wavelength, but large enough for adequate sensitivity to be achieved using practicable core materials and core dimensions. The rear gap should be made as small as possible, (zero if interleaving of laminations is possible) except in the infrequent cases where reducing h.f. core losses (see Section 5) may be more important than maintaining high sensitivity. Three examples may serve to illustrate the order of magnitudes involved in practice:

(a) Audio-frequency example: tape speed 15 in./sec, highest frequency 15 kc/s

b = 0·53 mil (6 dB loss at 15 kc/s)

l = 2 inch

μ = 20 000 (laminated mumetal)

a = 0 (rear of head interleaved)

A_b/A = 2/5

Sensitivity factor, S_b/S = 0·93

(b) High-frequency example: tape speed 100 in./sec, highest frequency 250 kc/s

b = 0·21 mil (6 dB loss at 250 kc/s)

l = 1 inch

μ = 800 (ferrite)

a = 0·01 mil (butt joint)

A_b/A = 2/5

Sensitivity factor, S_b/S = 0·29

(c) Video-frequency example: tape speed 200 in./sec, highest frequency 3 Mc/s

b = 0·035 mil (6 dB loss at 3 Mc/s)

l = 1 inch

μ = 800 (ferrite)

a = 0·01 mil (butt joint)

A_b/A = 2/5

Sensitivity factor, S_b/S = 0·065

In the latter case nearly all the reluctance is in the core so that the head is operating in the region where sensitivity is effectively proportional to gaplength and for every hundred lines of flux recorded on the medium, only about seven have a useful effect in the coils. It would, therefore, be desirable to reduce considerably the reluctance around the core by reducing the core length and by increasing its permeability, if possible. However, in practice a reduction of core reluctance is not easy for in high-frequency heads a ferrite with low high-frequency losses, and, hence, low permeability has to be used. A more promising approach is to decrease the factor A_b/A, i.e. to increase the taper at the pole-tips of the head. For instance, if in example (c) A_b/A is reduced to 1/10, the sensitivity is increased to 0·22. In an ideal system the gaplength would be increased until the opposing effects of gap-loss and increased overall sensitivity gave the optimum value of signal-to-noise ratio at the shortest wavelength of interest. In the high-frequency systems at present being developed, however, where technique is being strained to its limits, it is probably the reluctance of the core as a whole which is the dominating factor and which prevents full advantage being taken of the gaps obtainable.

3.1.2. Overall Dimensions of the Head.

The expressions for the reproducing response given in the previous section apply only as long as the pole-pieces of the reproducing head are capable of collecting all the flux available from a half-wavelength of tape in the peak output condition. If D (Fig. 2) is the overall dimension of the head in the direction of tape travel, then at wavelengths longer than this dimension, flux can be collected only from a length D of the relevant half-wavelength of tape, i.e. the reproducing response tends to decrease according to the factor $2D/\lambda$. The extreme low-frequency response of the head thus tends to fall with decreasing frequency at a rate of 6 dB/octave, as indicated by Curve (i) in Fig. 3.

An undulation may also be superimposed on the low-frequency response if the extremities of the head length D are too sharply defined in the neighbourhood of the tape. An extreme case is when the head has the configuration shown in Fig. 2(a). With this form of head the points where the tape meets and leaves the head are sharply defined and give rise to interference effects commonly called "secondary-gap effects". Provided λ is not greater than about $3D$, Westmijze has shown[3] that the secondary-gap effect is approximately expressed by multiplying the response by the factor

$$1 - 0{\cdot}205 \, \frac{\cos\left[\pi\left(D/\lambda + 1/6\right)\right]}{(D/\lambda)^{2/3}} \tag{12}$$

The calculated low-frequency response of a head of the type shown in Fig. 2(a) is indicated by Curve (ii), Fig. 3, plotted in terms of the parameter D/λ.

Such undulations in the response are normally undesirable and can be reduced by using the more usual configuration of head shown in Fig. 2(b). In this head, the area of pole-face in contact with the tape is not so well defined and the edges of the head are separated from the tape by a distance q. Very approximately the low-frequency response of this head is obtained by modifying (12) by a separation factor (see Section 3.1.4) to give

$$1 - 0{\cdot}205 \, \exp\left(-2\pi q/\lambda\right) \frac{\cos\left[\pi\left(D/\lambda + 1/6\right)\right]}{(D/\lambda)^{2/3}} \tag{13}$$

When $q = D/2$ the response approaches the smooth curve shown as Curve (iii) of Fig. 3.

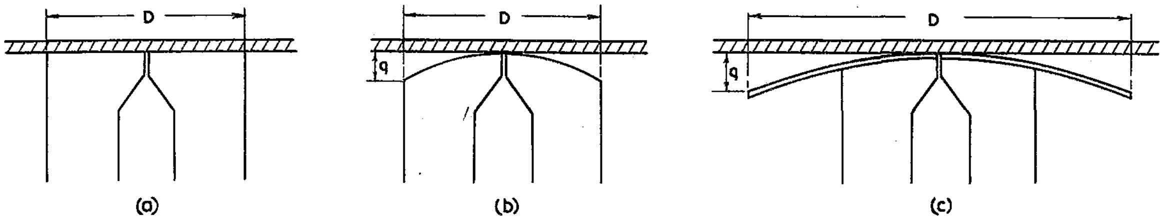

Fig. 2 - Plan views of three possible head configurations

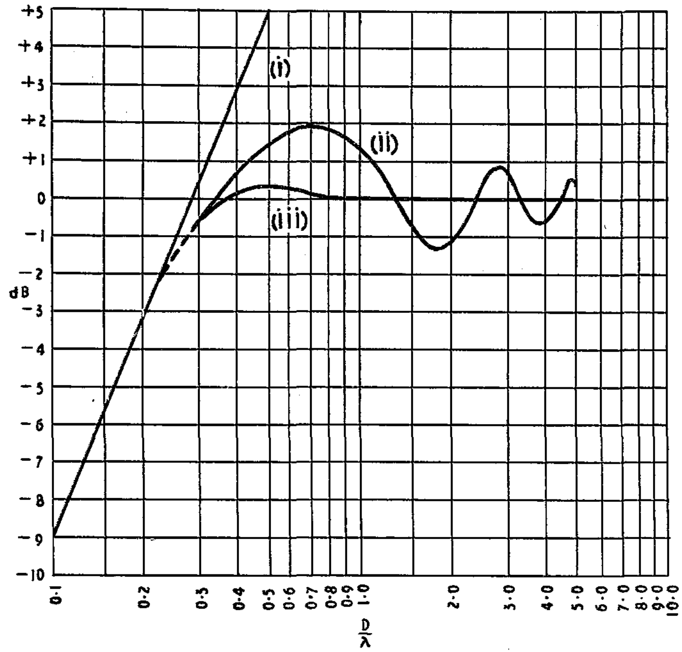

Fig. 3 - Low-frequency response curves of reproducing heads under various conditions

The longest wavelength that can be reproduced is still, however, limited by the overall length of the head. If only comparatively low frequencies are of interest, the core size can sometimes be increased so that wavelengths of several inches can be accommodated. This is not always desirable, or possible, however, especially when the effects of core size on head sensitivity (Section 3.1.1) or h.f. losses (Section 5) are important factors. In these cases a method of extending the long-wavelength response is to lengthen the head by adding high-permeability flanges or "wings" extending outwards on either side of the front surface of the head as shown in Fig. 2(c).

Finally it should be mentioned that secondary-gap effects may sometimes be attributable to causes other than the finite length of the front surface of the head[9]. Thus, at very long wavelengths, tape flux need not necessarily pass through the front surface to link with the head coils but may enter the coils by other paths. In some cases, careful attention must be given to points such as the disposition of the coils and the design of screening boxes if such effects are to be minimised.

3.1.3. Gap Misalignments.

The reproducing head will not be working at maximum efficiency at any wavelength unless both edges of its gap are correctly aligned with the trailing edge of the recording gap. The word "alignment" is not the happiest description of this requirement for three edges to be parallel but it has now become familiar in this context. If the edges of the reproducing gap are parallel but at a small angle θ to the trailing edge of the recording gap, the reproducing response β_θ is approximately given by[10, 7]

$$\beta_\theta / \beta_i = (\lambda / \pi w \theta) \sin (\pi w \theta / \lambda) \tag{14}$$

where β_i is the response obtained with correct alignment ($\theta = 0$). The effect of misalignment is thus analogous to gap loss (Section 3.1.1) and a serious maladjustment will give rise to cyclic amplitude and phase variations in the response corresponding to an effective gaplength $w\theta$.

At very short wavelengths, the alignment requirements become very critical. For instance, if the alignment loss is not to exceed 3 dB the requirements for quarter-inch wide tape are as follows:

(a) 15 kc/s, 15 in./sec, $\theta < 0{\cdot}1^\circ$

(b) 250 kc/s, 100 in./sec, $\theta < 0{\cdot}04^\circ$

(c) 3 Mc/s, 200 in./sec, $\theta < 0{\cdot}007^\circ$

The actual method of obtaining the necessary degree of alignment depends on the application. In some cases careful manufacture of the heads and their mountings, and careful machining of the base plate of the head unit, are sufficient. In other cases it is necessary to mount one of the heads on a rocking mechanism so that individual head units may be individually adjusted for the optimum result. The accuracy that can be achieved is, however, limited by three factors:

(i) The edges of the reproducing gap may not be parallel.

(ii) The edges of the reproducing gap (or the trailing edge of the recording head) may not be straight.

(iii) Inaccuracies may occur in guiding the tape across the heads.

The effect of the first factor has been discussed in detail elsewhere[7]. In general, if a reproducing head with a wedge-shaped gap is adjusted for optimum h.f. response it will be found that one edge of the wedge (it does not matter which edge) has been aligned with the recording gap. Under this condition — normally the only one of practical importance — the most obvious effect of making a gap wedge-shaped is to reduce the depth of the minima in the response curve attributable to finite gaplength. If the wedge is purposely made so that the "gaplength" at one side is very small compared with the shortest wavelength and, at the other side, is large compared with the longest wavelength, a response curve can be obtained free of excessive undulations over the whole working range[7]. Generally speaking, however, the response of a wedge-shaped gap is poorer than that of a comparable parallel-sided gap in an important part of the range below the first minimum so that wedge-shaped gaps are, usually, to be avoided.

The second factor is of considerable practical importance. Obviously if the edges of a reproducing gap are curved or irregular, there is no possibility of correct alignment with a straight-edged or differently curved recording gap; any adjustment made is bound to be a compromise between the conflicting requirements of different parts of the gaps. It will be found, moreover, that the optimum setting may vary considerably with the wavelength of the signal in making the adjustment[7]. Checking whether or not this variable-alignment property is present is, in fact, a good way of testing whether a pair of heads has been accurately manufactured.

The third factor arises from the necessity of allowing some clearance in the guides on either side of a head in order that the tape may pass through them unhindered. If, at some instant, the tape is touching the top edge of one guide and the bottom edge of the next, it must be making an angle with the intended direction of motion through the centre of the guides. Obviously there can be an uncertainty of twice this angle in the effective head alignment. The tolerance on the width of quarter-inch tape is normally +0, −6 mil, so that if the guides are 2 inches apart the relevant angular error can be as high as 0·34° without allowing the guides to have any positive clearance at all. Such an error would create variations of output level from the maximum (at correct alignment) to zero in each of the examples (a), (b) and (c) given above. The angular error would obviously be reduced if the distance of 2 inches between the guides on either side of the head were increased. The importance of choosing the distance with reference to the variations in the width of the tape is obvious.

3.1.4. Separation between Head and Tape.

In discussing other factors affecting the reproducing response it has been assumed that the surfaces of the head and tape have been in perfect contact in the region of the front gap. If this is not the case, but they are separated by a distance d, the reproducing response becomes[11, 3] β_d where

$$\beta_d/\beta_i = \exp(-2\pi d/\lambda) \tag{15}$$

The effect of a given separation becomes increasingly severe, therefore, as the wavelength becomes shorter. At any wavelength the loss in decibels is proportional to separation, and the loss for a separation equal to a wavelength is equal to 54·5 dB. The following examples of the rate of loss due to separation will serve to illustrate the importance of the effect:

(a) 15 kc/s, 15 in./sec, 5·5 dB per 0·1 mil,

(b) 250 kc/s, 100 in./sec, 13·6 dB per 0·1 mil,

(c) 3 Mc/s, 200 in./sec, 81·5 dB per 0·1 mil.

From these figures it is apparent that great care must be taken in the surface finish of heads designed for short-wavelength work. The pole pieces and gap spacer should be accurately aligned and polished and care must be taken to avoid indentations or crevices (such as those between badly assembled laminations) which might cause particles of dust or tape coating material to build up and lift the tape off the head. Also, of course, adequate pressure between head and tape must be provided by either a suitable combination of tape tension and lap or (less desirably) by means of pressure pads. Variations in contact due to shortcomings of the tape itself, such as those due to

irregularities in the coating surface, will be discussed under a separate heading (Section 4.1).

In some systems, such as those involving high-speed storage drums, a separation between the heads and recording medium may have to be introduced to avoid wear. It is apparent, however, that the short-wavelength range of such devices is bound to be greatly limited by the separation effect, even if the separation has a value that would be thought extremely small in mechanical engineering terms.

3.2. The Factors Governing the Recording Response.

3.2.1. Tape Thickness.

In many applications the shorter wavelengths encountered may be comparable with, often less than, the thickness of the magnetic coating on the tape. This causes a departure from the ideal performance which, physically, is closely associated with the reproducing process and the exponential nature of the separation loss. When recorded level is defined in terms of surface induction, however, the effect of an appreciable tape thickness must be considered part of the recording process and the recording response is modified[11] from the ideal value α_i to a value α_c where

$$\alpha_c/\alpha_i = (\lambda/2\pi c)[1-\exp(-2\pi c/\lambda)] \qquad (16)$$

assuming the magnetisation at all wavelengths to be uniformly distributed throughout the cross-section of the magnetic coating.

At long wavelengths $\alpha_c/\alpha_i \approx 1$ and the response approximates to the ideal which rises at 6 dB/octave with signal frequency. At very short wavelengths, however, $\alpha_c/\alpha_i \approx \lambda/2\pi c$, implying a 6 dB/octave loss with signal frequency and a consequent flattening of the observed h.f. response. For a uniformly magnetised tape of coating thickness 0·5 mil the calculated differences between the actual and ideal recorded levels at (a) 15 kc/s, 15 in./sec, (b) 250 kc/s, 100 in./sec and (c) 3 Mc/s, 200 in./sec amount to 10 dB, 18 dB and 33·5 dB respectively.

In effect, the surface induction at long wavelengths is created by substantially equal contributions from all layers of the magnetised coating, but the surface induction at short wavelengths is almost entirely created by a thin layer near the surface. When recording in a restricted range of short wavelengths, such as occur in some carrier systems, it may, therefore, be possible to reduce the coating thickness without affecting the recorded level. This may result in economy in the cost of tape and an increase in playing time for a given spool diameter.

3.2.2. Self-Demagnetisation in the Tape.

In addition to the useful external field, which is intercepted during reproduction, a magnetic field must also exist within the recorded tape. In general, the internal field is in opposition to the magnetisation creating it and may cause a reduction in the intensity of this magnetisation and a corresponding reduction in surface induction. In simple cases of self-demagnetisation, J and H', the intensities of the magnetisation and the internal field have the same distribution and there is a constant coefficient of self-demagnetisation $Z = H'/J$. Under these conditions the reduced value, J', of the intensity of magnetisation is given by

$$J'/J = 1/(1 + Zk) \tag{17}$$

where k is the susceptibility of the magnetic material. The maximum possible value of Z is equal to 4π (corresponding to a large sheet of thin material magnetised perpendicularly to its plane) and the greatest reduction in magnetisation is consequently equal to $1/\mu$.

In a recorded tape, the magnetisation and demagnetising field may have very different distributions through the depth of the tape and a precise calculation of the self-demagnetisation loss cannot easily be made. An indication of the effect may, however, be obtained by calculating the mean value of Z throughout the tape. Thus, for a tape magnetised uniformly in the longitudinal direction, the mean value of Z is given by[2]

$$Z = 4\pi\{1 - (\lambda/2\pi c)[1 - \exp(-2\pi c/\lambda)]\} \tag{18}$$

The mean coefficient of self-demagnetisation is thus negligibly small at long wavelengths, but increases as the wavelength becomes comparable with tape thickness until, when $\lambda \ll c$, it tends towards a limiting value of 4π. According to (17), the self-demagnetisation loss cannot, therefore, exceed a value of $1/\mu_t$ where μ_t is the permeability of the tape material.

In practice, the true self-demagnetisation loss at short wavelengths will be considerably less than is indicated by this simple treatment of the problem. For instance:

(i) The magnetisation may not all be in the longitudinal direction but may have an appreciable component perpendicular to the tape surface. Self-demagnetisation of the perpendicular component will be confined largely to long wavelengths[3].

(ii) The demagnetising field strength, assumed constant in the derivation of (18), is actually much lower near the surface than it is near the centre

of a tape magnetised longitudinally. This is of importance since, as discussed in the preceding section, the useful magnetisation at short wavelengths may be confined to a layer near the surface.

(iii) The effect of a high-permeability reproducing head core should be to reduce the coefficient of self-demagnetisation very nearly to zero in the longitudinal case[3]. Thus, on reproduction, the loss in the recording response should be considerably reduced.

The last point can be used to provide experimental evidence of the magnitude of the self-demagnetisation loss. If the loss were serious, the recording response of a system measured by means of a conventional reproducing head and a non-magnetic conductor head should be markedly different. In fact, using normal tapes, the responses are substantially the same[12].

Many early authors attributed the major part of the h.f. loss in the magnetic recording response to self-demagnetisation and specified high coercivity as the controlling magnetic property in obtaining a good h.f. response. It now appears that these conclusions were inaccurate: self-demagnetisation probably contributes only a small part of the total loss and the relevant magnetic property is the permeability, rather than coercivity, of the tape material. The values of μ_t seldom exceed 3 or 4 in the commonly used tape coating materials.

3.2.3. Non-Uniform Recording Field.

So far it has been assumed that the recording field is uniformly distributed throughout the depth of the tape. In most cases, however, the recording field strength H will decrease appreciably with distance y from the surface of the head. For instance, if H_0 is the strength of the field within the gap, the maximum strength H_x of the longitudinal field outside the gap is approximately given by[2,13]

$$H_x/H_0 = (2/\pi)\tan^{-1}(b'/2y) \tag{19}$$

For reasons to be given in the two following sections it is undesirable to make the gaplength b' very large. It follows from (19), however, that a gaplength small compared with the tape thickness c will lead to a marked decrease in the signal and bias field strengths through the tape. Often the recording gaplength is made approximately equal to the tape thickness, normally 0·5 mil. Even so, the longitudinal field strength at the base of the coating will be less than half that at the outer surface.

The decrease of the signal field strength through the depth of the tape is less important than the decrease of the bias field strength, for non-uniformity of bias field strength means that it is impossible to bias correctly the whole of the tape. With serious non-uniformity of field, two extreme cases arise:

(i) The bias may be adjusted so that the outer layers are correctly biased. In this case the inner layers may be grossly underbiased. The recording on these inner layers may, therefore, be very non-linear and, bearing in mind that the signal field strength has fallen also, the level of the inner layers may be very low. These effects will not greatly affect

short-wavelength work since the useful magnetisation is confined to the surface layers. They may, however, greatly detract from the performance at long wavelengths ($\lambda > c$).

(ii) The bias may be adjusted so that the inner layers are correctly biased. In this case the outer layers may be grossly overbiased, leading not so much to distortion in these layers, but to a reduction in their intensity of magnetisation. The effect of this is contrary to that of the previous case in that a greater loss will now occur at short wavelengths for which the outer layers are relied upon for the major contribution to surface induction. This effect can be used to explain, in part, the fact that short wavelengths are more easily overbiased than long wavelengths, particularly when the tape thickness is large compared with the gaplength of the recording head[2]. This subject is further discussed in Section 3.2.4.

To summarise, the recording gaplength should be made as large as possible whilst having regard to the considerations to be discussed in Sections 3.2.4 and 3.2.5. An unnecessarily small recording gaplength will, when the bias is adjusted to avoid excessive short-wavelength losses, generally entail a needless decrease of sensitivity and linearity in the long-wavelength recording region. If attention is strictly confined to very short wavelengths, however, a short gaplength may be an advantage.

3.2.4. Rate of Extinction of Recording Field.

In the brief discussion of h.f. bias given in Section 2.3 it was suggested that in conditions of adequate biasing the final remanent magnetisation of an element of tape leaving the recording head is decided at the point where the bias field strength has fallen to a certain critical value h_c. This might indeed be accurately the case for an element of tape consisting of a single particle or magnetic domain. In general, however, all the particles in the magnetic coating will not be identical in form and cannot be expected to require identical values of h_c. Indeed, as pointed out by Westmijze[3], if there were a unique value of critical field the sensitivity-bias curve should rise vertically to its maximum value instead of rising with a finite although steep slope as it does in practice.

This modification of the hypothesis will not materially affect the linearising action of the bias. It will, however, affect the second attribute of bias, namely that it creates conditions in which the recording signal field experienced by a given element of tape can be regarded as single valued. For instance, suppose that the distribution of h_c is such that if $p\delta h$ is the number of particles having a value of critical field between h and $h + \delta h$, p is a constant over the range $h_1 < h < h_2$ and zero outside this range. Then recording will no longer take place at a discrete point but over a distance ξ equal to the distance the element must travel from the gap in order for the bias field strength to fall from h_2 to h_1. Ignoring the fall in instantaneous signal field strength over this region, the effect would obviously be analogous to an aperture loss of the form

$$a_\xi / a_i = (\lambda/\pi\xi)\sin(\pi\xi/\lambda) \qquad (2.)$$

and would have no appreciable effect on the recording response at long wavelengths but would cause a serious loss when λ becomes comparable with ξ. In practice, of course,

the signal field strength will fall to the same extent as the bias field strength over the critical range. Also the distribution function ϕ is not likely to be as simple as that assumed above*. Nevertheless, it may be of interest to mention that series of minima can be observed in the recording response at short wavelengths and high bias levels. These minima appeared to be unrelated to known gap phenomena and their position was found to depend very much upon bias level.

Now the distance ξ will depend upon the rate of extinction of the recording field. If this could be made instantaneous, ξ would be zero. If, on the other hand, the decay of field were very slow compared with the period of the signal, the combined signal and bias recording fields might act simply as an erasing field and the tape would emerge from the recording head in a neutral condition. In practice, therefore, the rate of extinction should be made as high as possible, a conclusion supported by the experiments of Muckenhirn[15]. Even with very short gaplengths, however, the rate may still be significant and a substantial part of the h.f. loss of biased systems can probably be attributed to the "critical range effect". Alternatively, of course, the distance ξ is made smaller as the range, $h_2 - h_1$, of critical fields required by the coating becomes smaller. If all particles required the same critical field, h_c, the rate of extinction of the recording field would be unimportant and no h.f. loss should result from it.

A secondary effect of considerable importance is that the distance ξ will also depend upon bias current. This arises because the decay of the bias field on leaving the gap is not uniform, but tends to fall more steeply at first. If, therefore, the bias current in the head is raised, the limits of the critical range are moved further away from the gap and are spaced further apart on a more gradually sloping part of the bias field decay curve. This may account for the fact that short wavelengths are found to be much more easily overbiased than long wavelengths, even when recording gaps substantially greater than tape thickness are used and the effects noted in Section 3.2.3 cannot play a large part. In practice, the short-wavelength overbiasing phenomenon often imposes a very serious limitation on the performance of biased systems. The bias current invariably has to be adjusted to avoid serious h.f. loss on the one hand and l.f. insensitivity and distortion on the other; whatever compromise is selected a significant deterioration in performance is inevitable.

3.2.5. Interference Effects in the Recording Gap.

If good linearity of response is required, the use of h.f. bias in recording is essential but the discussion in the preceding two sections indicates that there are also certain disadvantages, particularly when short wavelengths are to be recorded. In some applications a good response at very short wavelengths is a more important requirement than linearity and the use of an unbiased system is then possible. This may occur, for example, when the recorded signals are to be short pulses of constant amplitude.

It has been shown[5], however, that the recording field affecting the tape when h.f. bias is absent is not single-valued and serious interference effects may then

*Osmond[14] assumes a Gaussian distribution of particle shape in explaining the hysteresis properties of tape materials with considerable success, and there is probably a close relation between critical field strength and particle-shape anisotropy.

occur in the recording gap. These give rise to undulations in the recording-frequency characteristic which are related to the finite length of the recording gap, with minima occurring when the gaplength $b' \approx 3\lambda/4$, $7\lambda/4$, etc. In pulse-recording work the phase distortion aspect of these undulations may be of greater importance than the amplitude variations: an amplitude variation of only 2 dB may be associated with a phase effect of prohibitive magnitude in some applications. It has also been shown[5] that the effect of adding and increasing bias is gradually to eliminate the minima but, unfortunately, they cannot always be entirely removed before an appreciable over-biasing of the shortest wavelengths occurs due to the secondary effects discussed in Sections 3.2.3 and 3.2.4. The interference phenomena in the recording process may, therefore, also be of significance in systems in which, perhaps, to avoid h.f. over-biasing, too low a value of h.f. bias is used in conjunction with an appreciable gap-length.

A conclusion of considerable importance to draw from this discussion is that when, for various reasons, a recording system is to be used with little or no h.f. bias then the gaplength of the recording head should be small enough for the condition, say, $b' < \lambda_s/2$ to obtain, where λ_s is the shortest wavelength to be recorded.

3.2.6. Separation between Head and Tape.

The surface of the tape may be intentionally or accidentally separated from the surface of the head for reasons similar to those described in Section 3.1.3 in connection with the reproducing head. The effect of such separation is more complex, but generally less serious, than in the reproducing head case. Two principal effects can be envisaged:

(i) A separation will cause a fall in the strength of both the signal and bias fields and a consequent general loss in recording response. The effect will be most marked if, when in contact, the bias field strength was only just sufficient to give maximum sensitivity.

(ii) A separation will cause a lower rate of extinction of the recording field, since the leakage flux is more widely spread over planes removed some distance from the gap. This, according to the arguments of Section 3.2.4 may cause a large loss at the shorter wavelengths. Normally, however, the magnitude of this loss is not large compared with that arising from an equivalent separation of the reproducing head.

4. AMPLITUDE AND SPEED FLUCTUATIONS.

4.1. The Effect of Amplitude Fluctuations.

The amount by which the level of a signal may be decreased before it becomes effectively unusable depends normally on the noise associated with it. In assessing the ability of a recording system to store a signal involving extremely short or long wave-lengths, therefore, the factor of interest is the signal-to-noise ratio in the final output, so that a decrease in noise level can be as valuable as an improvement in signal level. The output voltage of the reproducing head being so small, a minimum amount of noise must be introduced by the input circuits of the reproducing amplifier. The

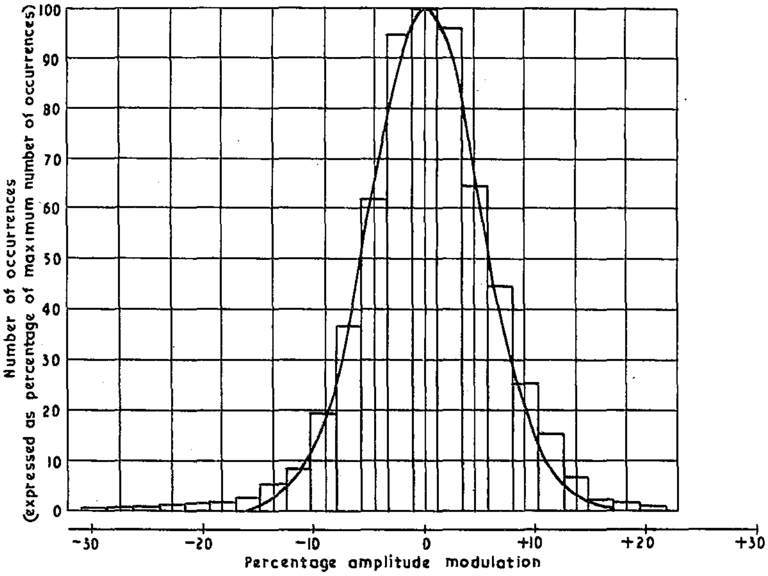

Fig. 4 - Distribution of amplitudes in modulation envelope of recorded 10 kc/sec tone

Period of observation: 10 sec.

voltage from the head itself, however, contains components of noise—"modulation noise"—which are contributed in recording and reproducing due to undesired amplitude fluctuations superimposed on the input signal in these processes. A typical distribution of amplitudes in the varying (nominally constant) envelope of a 10 kc/s tone, recorded and reproduced at 15 in./sec on a commercial tape of average quality, is shown in Fig. 4. Analysis of these typical fluctuations indicates that they are largely random in nature so that they contribute a true noise voltage to the input signal and so reduce the signal-to-noise ratio. In the following paragraphs some consideration will be given to the causes of these fluctuations to assess how far they are fundamental and how far they may be reduced by careful design and manufacture of the components of the system.

4.2. Factors Causing Amplitude Fluctuations.

4.2.1. The Particle Nature of the Coating.

In most modern systems the material which forms the recording medium consists of small particles of various magnetic oxides of iron, sometimes with the addition of some iron powder. These components are thoroughly mixed together with a suitable binding agent and are coated on to one side of a plastic tape, or other surface, as required. The medium may be expected to consist, therefore, of crystals which vary

(a) in size and shape,
(b) in orientation,
(c) in separation from one another.

In this connection Osmond[14] has shown that the observed values of intrinsic coercivity for fine powder dispersions of iron oxides used in the recording medium can be satisfactorily explained on the assumption that the powder particles are all of single domain dimensions and of random orientation and shape factor whilst there is some evidence[16] that the particles in the medium are not always evenly distributed through

the binding agent but are grouped in clusters. It follows that the variations of magnetisation within any one recorded wavelength cannot take place smoothly and continuously but must occur in a series of discrete steps or jumps, the magnitude of which depends on the size, shape and orientation of the various particles and on their distribution. The size of the domain might impose an ultimate limit on short-wavelength recording for, clearly, no frequency corresponding to a half-wavelength shorter than the average size of domain could have a sensible effect on the medium. This ultimate limit cannot be achieved, however, whilst the particles, even if single domains, are separated by some finite distance due to the presence of the binding agent. The ultimate half-wavelength limit is then larger by a factor depending on the average separation of particles, i.e. the "packing factor". In practice, however, the large random variation in packing factor, demonstrated by Westmijze, will create an even earlier limitation, for the random variation of amplitude which it must impose on the recorded signal will appear as noise in the reproduced output and the detection of signals below some critical level is eventually rendered impossible. These coating variations will, of course, particularly affect the signal-to-noise ratio in the short-wavelength region in which only a thin surface layer of the tape is employed. The effect at longer wavelengths should be less severe if the lack of uniformity in size, packing and orientation is the same at all depths within the coating, for the greater the number of layers contributing to the output the less will be the relative effect of a variation of signal in any one of them.

4.2.2. Irregularities in the Surface of Backing.

Another contribution to the noise discussed in the previous paragraph is made when the surface of the flexible, or other, backing on which the medium is supported is irregular. Lack of smoothness in the backing creates a gross variation in the dispersion of the particles at the base of the coating and this will assume importance when the under layers are significant in the recording and reproducing processes. This will be the case at long wavelengths providing that the signal and bias fields from the recording head are such as to create an appreciable magnetisation at the base of the coating. This effect accounts for the comparatively high modulation noise which occurs in tapes with paper backing, compared to those with plastic backing, the fibrous nature of paper making it difficult to attain the same degree of smoothness that can be obtained with a plastic material.

4.2.3. Variations of Contact between Head and Tape.

The level of signal appearing at the terminals of the reproducing head has been shown to depend on the effective separation of the recording medium from the heads in the recording and reproducing processes. The variation of recorded level with separation depends on the recording gapwidth and the coating thickness but not, in the usual case, on wavelength. Change of separation from the reproducing head, however, causes a variation of level dependent on wavelength according to the factor $\exp(-2\pi d/\lambda)$ which is, therefore, especially large at short wavelengths. In practice undesired changes in the separation of the tape from both heads will occur for several reasons and when these changes are random they constitute another source of modulation noise.

The lack of uniformity in the size, packing and orientation of particles in the coating, which has been discussed in Section 4.2.1, will also imply a lack of perfect flatness at the surface so that the effective separation of the tape from

the heads must vary about an average value in a manner depending on the random variations in the particle projections. This variation, and the modulation noise which it creates, may be reduced by suitable polishing of the tape surface after manufacture, and the beneficial effects of this will be very evident at short wavelengths. Particular attention must also be paid to the smoothness of the head surface, however, so that it does not contribute to the effective separation between the mass of the high-permeability core and the tape coating. A rough head surface will tear particles out of the coating resulting in variable separation as the particles are carried over the head surface. In extreme cases the coating debris may collect in the indentations in the head surface and the subsequent "build-up" of material will create a gross separation of tape and head.

Fluctuations of amplitude may also arise when particles of dust adhering to the surface of the tape are carried over the heads. In this connection a build-up of static charge on the tape, which attracts dust particles to the surface, may be an important factor. Some plastic backings acquire a static charge, especially at high tape speeds, due to the effect of friction in passing over non-conducting tape guides and pulleys. Apart from its power to attract dust particles this static electricity may discharge on the earthed surface of the head and induce noise in the reproducing head. In such cases it is important that the tape should be discharged before reaching the reproducing head and that the atmosphere of the enclosure in which the system is operating should be free from dust as far as possible.

Finally, mechanical inaccuracies in (a) the tape, and (b) the driving system, may vary the effective separation between tape and head surfaces. With reference to (a), the difficulties which arise in attempting to guide a tape accurately past the heads when its width varies have already been noted. Here it is only necessary to recall that if a portion of tape is wider than the guides adjacent to the head then the tape must bend and leave part, or all, of the head surface if it is to be accommodated in the guides. A fluctuation of amplitude then occurs of a magnitude and frequency which depends on the variation of width along the length of the tape. As regards (b) the inaccuracies in the driving system, such as eccentricities in capstans or pulleys, will manifest themselves as slight changes of driving speed. With these changes of speed (which will themselves be discussed later) will almost certainly be associated changes in the tension of the tape over the heads. A change of tension may in turn cause a fluctuation in the effective separation from the head and hence in the recorded and reproduced levels of signal.

4.3. The Effect of Speed Fluctuations.

Exact reproduction of the frequencies or frequency changes in the signal fed to a recording system requires that the speed of the recording medium past the heads at each point in the record is exactly the same in the recording and reproducing processes. Most magnetic recording systems, and all of those which employ magnetic tape, are constant speed systems, i.e. the tape speed should be the same at all points of the record and in both the recording and reproducing processes. A temporary departure from correct speed in recording creates a temporary change of wavelength on the tape which appears as a change of frequency when the tape is subsequently reproduced at constant speed. During a departure from correct speed in the reproducing process the recorded waveforms pass the reproducing head at a rate different from the recording process so that the frequency of the output is altered accordingly. In each case,

therefore, the effect is an unwanted frequency modulation of the original signal. In practice, even in a well-designed system, the speed is never perfectly constant for an appreciable period and the reproduced signal contains the effects of speed changes in both the recording and reproducing processes. In a tape recorder the speed changes are attributable to mechanical imperfections of the tape transport system and to interactions between the moving tape and the transport system. Certain well defined frequencies of modulation may, therefore, be present but it has been shown elsewhere[17] that in systems of this kind a large random element may also be observed. As such the frequency modulations represent an addition of noise to the signal which will reduce the low-level limits of the system and its ability to provide accurately synchronised information when required. In the next few paragraphs the origin of these speed changes will be examined and measures which may be taken to reduce them will be briefly discussed.

4.4. Factors Causing Speed Fluctuations.

4.4.1. The Tape Transport System.

The conventional layout of a tape recording system is illustrated in Fig. 1(a) the drive being obtained from a rotating capstan against which the tape is held by a spring-loaded rubber idler. In practice the compressible idler will allow the tape to sink into its surface and the idler itself will make contact with the capstan. A large, possibly the major, proportion of the driving torque on the tape is, therefore, provided by the rubber idler rotating against the back of the tape, the actual proportion depending on the hardness of the rubber and the loading pressure employed. Clearly the compressibility of the rubber should be uniform around its circumference so that no change of driving torque occurs in the course of a revolution. The rubber comprising the idler should, therefore, be free from "hard spots" and, in so far as compressibility may in some measure be dependent on radius, the idler should be free from major eccentricity. If no slip takes place the tape is then driven at a speed equal to the peripheral speed of the capstan so that the capstan itself must be accurately circular and rotate at constant speed.

Rotation of the capstan at constant speed requires high accuracy in the bearing system in which it is supported and a corresponding speed constancy in the motive system by which it is driven. The latter is commonly a synchronous electric motor which is either coupled to the bottom of the capstan shaft directly through flexible couplings or indirectly through a belt and pulley, friction-drive or gear system. The particular method chosen depends upon the rotational frequency required at the capstan compared with the frequency of rotation of the driving motor. In all cases a massive fly-wheel may be mounted at the base of the capstan shaft to smooth out the more abrupt or high-frequency changes of speed which may result from imperfections of the driving system. The most accurate results are obtained by the use of the simpler, direct drive and here the requirement is for a high-quality motor, with accurate bearings, the axis of which is correctly aligned with the axis of the capstan shaft. The indirect drives are fundamentally more subject to error but, as in the simpler case, if the best results are to be obtained the motor must be of high-quality and all rotating or moving parts such as shafts, pulleys, and belts must be accurately made and fitted.

If, in the approach to the driving point, there is an appreciable "wrap-round" of tape on the idler then any eccentricity in this element will vary the speed of the

tape past the heads, although at the driving point the speed may be more nearly constant. Since, in general, it is easier to obtain high accuracy in the capstan than the rubber idler, and the latter is less stable, the tape should be brought into contact with the capstan, and not the idler, before the driving point is reached.

If the pressure of the idler on the capstan is sufficient the tape passing over the heads should be largely isolated from any torque changes emanating from the take-up spool, and its motor, beyond the driving point. The same is not true, however, of the feed-spool system and any sudden fluctuations in the opposing torque (which is necessary to keep the tape in contact with the heads) emanating from there will be reflected in the velocity of the tape passing over the heads. Changes in the opposing torque may arise if there are eccentricities in the feed-spool system, if the tape comes into accidental contact with the sides of the spool, or when adjacent layers of the tape stick to one another due to dirt or careless handling. Fluctuations also arise if there are eccentricities in any pulleys which guide the tape onto the heads. Some measure of isolation at the heads from imperfections of this nature may be achieved by the provision of a mechanical filter in the position indicated in Fig. 1(a). This filter usually consists of a spring-loaded jockey arm to the shaft of which is attached a suitable mass. Correct choice of the mechanical constants will enable the more common and troublesome torque changes to be attenuated in the filter.

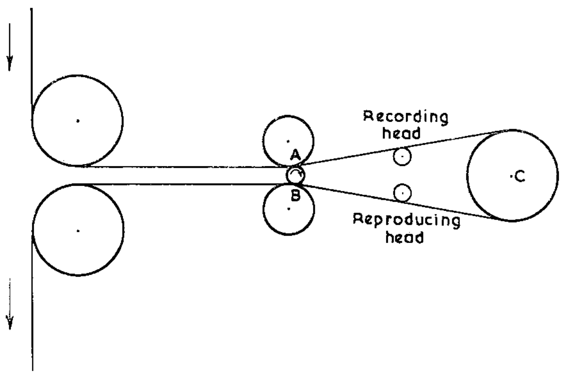

Fig. 5 - "Double-pinch" driving system

It is of interest to observe that in an alternative drive system, which is sometimes used, isolation from both take-up and feed spools is possible. In this system, the essentials of which are illustrated by Fig. 5, the tape is driven by the capstan at two points, A and B, and passes over a pulley C between them. The recording and reproducing heads may be mounted at convenient points inside the loop so formed. Here the standard of accuracy required in the capstan and rubber idlers is the same as in the single driving-point system and the pulley C must be manufactured to the same degree of accuracy as the capstan. The isolation properties of this design can be valuable and it is fundamentally less subject to some interaction effects of the type to be described in the following paragraph.

4.4.2. Interaction between Tape and Transport System.

The small, but significant, variations of width which may exist along the length of the tape and which have been discussed in several other contexts, are also important as a source of speed fluctuations. Accurate guiding requires, ideally, that the guide width should be identical with the nominal width of the tape but in practice some tolerance must obviously be allowed. When a length of tape occurs which is wider than the guide the frictional forces between the edges of the tape and guide become large. On the other hand, when a length of tape occurs which is narrower than the guide the edge frictional forces are confined to one edge only or may even be

absent altogether. If the width of the tape varies in a random manner an appreciable random component must then be present in the frictional forces existing between the tape guides and the tape edges. When the length of tape over the heads is not isolated from these forces then the velocity of the tape in this region must vary accordingly.

In the simple conventional form of static tape guide the surface of either the backing or the coating also comes into contact with the face of the guide in passing through it and another set of frictional forces is set up. A similar set is also generated as the tape passes each head. The random conditions in the surfaces of either coating or backing, which have been noted in discussing amplitude modulation, will vary these forces so that another random element is present in the system. The surface friction in the guides will be eliminated if they are so designed and positioned that the tape comes into contact with them only at its edges or if the guides take the form of pulleys which are driven by the tape.

The existence of surface friction forces, and their reduction by the measures described is equally significant in tracing the origin of another distinctive set of higher-frequency fluctuations, which may be observed under critical conditions. These fluctuations, which have been investigated by Werner[18] result from a longitudinal oscillation of the tape over the heads at a frequency which is a function of the elasticity of the tape, its density and the particular transport system employed. Werner has shown that static elements, such as heads and conventional guides, may act as generators of oscillations along the length of the moving tape, the excitation being provided by the frictional forces. These oscillations can be of large amplitude at a frequency of resonance determined by the length of tape between any two adjacent "bridge" points such as, for example, the guide pulley situated before the heads and the driving point on the capstan which follows them. If no slip is occurring each of these points has zero speed relative to the tape and they represent bridges or nodes between which the oscillations are propagated. If s is the distance between the nodes, the frequency of the oscillation is given by $f = (1/2s)\sqrt{D/\rho}$ where D is the modulus of elasticity and ρ the density of the tape in kilogrammes per cubic metre. In practice the frequency of these oscillations is found to lie between 1 and 3 kc/s and their amplitude may be shown to vary with the coefficient of friction of the tape and the tape tension, the latter determining the pressure on the heads and, hence, the frictional forces set up. The effect is particularly large in machines which have a number of conventional guides adjacent to the heads or in which contact between the heads and tape is maintained by pressure pads. The oscillations will be reduced in a conventional system if the following requirements are observed:

(a) the tape tension is reduced as far as possible, consistent with adequate contact,

(b) the coefficient of friction of the tape is made as small as possible,

(c) no slip is allowed to occur at the pulleys or the capstans,

(d) the fixed guides do not touch the tape except at the edges, and

(e) the head surfaces, which must be the only static surfaces in contact with the tape surface, are extremely well polished.

The tape tension and other factors cannot usually be adjusted to eliminate this phenomenon completely and some longitudinal oscillations may always remain. Werner

has described how these may be further reduced by "loading" the tape, at one or more convenient points between the heads, with rotating pulleys in which no slip takes place. It is also desirable to mount the heads near the drive system and make the distance between the various heads as small as possible. All these measures tend to generate the oscillations at higher frequencies at which they are more severely attenuated. When loading pulleys are introduced they must be of high accuracy to ensure that they do not introduce periodic fluctuations on their own account.

5. HEAD CORE LOSSES AND RELATED DESIGN PROBLEMS.

5.1. Nature of Core Losses.

It has been noted (Section 3.1.1) that the sensitivity of a reproducing head is proportional to the ratio of front gap reluctance (S_b) to total reluctance (S). The sensitivity of a recording or an erasing head may be defined in terms of the field strength produced in the gap for a given current in the coils and is, then, proportional to $1/S$. Thus, for all types of heads the ratio of the sensitivity σ_f at a frequency f to the sensitivity σ_o at zero or very low frequencies is given by

$$\frac{\sigma_f}{\sigma_o} = \frac{S_o}{S_f} \tag{21}$$

This assumes that the reluctance of the gap remains constant but that the total reluctance of the head increases from S_o to S_f as the frequency is raised from zero to the value f. Such an increase is attributable to the fact that, as the frequency is raised, an increasing amount of energy is absorbed in eddy current, hysteresis and "residual" losses in the core. These losses are accompanied by a lag in phase and can be described by considering that the effective permeability of the core changes from a real value μ_o at zero frequency to a complex quantity μ_f at a frequency f where

$$\mu_f = \mu' - j\,\mu'' \tag{22}$$

Considering the head to have a front gaplength b, a rear gaplength a, a core length l, and a cross-sectional area A throughout, (21) can be written

$$\frac{\sigma_f}{\sigma_o} = \frac{b + a + l/\mu_o}{b + a + l/\mu_f}$$

$$= \frac{\gamma + 1/\mu_o}{\gamma + 1/\mu_f} \tag{23}$$

where

$$\gamma = \frac{b + a}{l} \tag{24}$$

[Often the core is tapered towards the front gap so that the cross-sectional area A_b of the front gap is considerably less than A. When necessary, this can be taken into account by replacing b by bA/A_b in (24)].

Substituting for μ_f in (24) and rationalising

$$\left|\frac{\sigma_f}{\sigma_o}\right| = \frac{\gamma\mu_o + 1}{\gamma\mu_o}\left\{\frac{(\gamma\mu')^2 + (\gamma\mu'')^2}{(\gamma\mu' + 1)^2 + (\gamma\mu'')^2}\right\}^{\frac{1}{2}} \tag{25}$$

and the angle ϕ of the phase lag is given by

$$\tan\phi = \mu''/\{\gamma[(\mu')^2 + (\mu'')^2] + \mu'\} \tag{26}$$

It is apparent from (25) that the head sensitivity remains substantially constant provided $\gamma\mu' \gg 1$ or, in other words, provided the reluctance of the core is always small compared with that of the gaps. In general, therefore, the effect of core losses can be minimised by (a) making the front gaplength as large as possible without causing severe interference effects at the shortest wavelength, (b) introducing an appreciable gap in the rear of the head if absolute sensitivity requirements will allow it and (c) making the core as short as possible and of a material of high permeability and low-loss over the required frequency range. In connection with (b) it should be realised that the effect of core losses is reduced by the presence of a rear gap only at the expense of a loss in absolute sensitivity equivalent to multiplying the response by the factor

$$\frac{b + l/\mu_o}{a + b + l/\mu_o} \tag{27}$$

This loss of sensitivity can, in the case of recording heads, be made up by increased recording currents and here the larger rear gap may be well worthwhile for, in addition to reducing the effect of core losses, it also tends to reduce the effects of non-linearity in the core. A large rear gap is, however, seldom acceptable in the case of reproducing heads where absolute sensitivity is generally of over-riding importance. If the rear gap is negligible, $\gamma = b/l$, and the sensitivity of the reproducing head at a given frequency is proportional to the factor

$$\frac{\gamma\mu_o}{\gamma\mu_o + 1} \cdot \left|\frac{\sigma_f}{\sigma_o}\right| = \left\{\frac{(\gamma\mu')^2 + (\gamma\mu'')^2}{(\gamma\mu' + 1)^2 + (\gamma\mu'')^2}\right\}^{\frac{1}{2}} \tag{28}$$

5.2. Measurement of Core Losses.

Two methods of measuring the effect of core losses on performance are in common use, particularly in connection with frequency characteristic standardisation. The first, and perhaps the most direct, method relies upon separating the losses that fundamentally depend on frequency from those that fundamentally depend on wavelength by taking measurements of overall response at a variety of tape speeds. In the second method an alternating flux is induced in the head from a small conducting loop or coil placed near the front gap and core losses are determined by measuring the departure of the e.m.f. generated in the head-coil from a 6 dB/octave law.

In many cases, however, it may be more convenient to assess the magnitude of the losses from bridge measurements of the way in which the impedance of the head varies with frequency. Thus, if L_o and R_o are the values of the series inductance and resistance at zero frequency and L_f and R_f the effective values measured at a frequency $f = \omega/2\pi$, then

$$\frac{S_o}{S_f} = \frac{j\omega L_f + R_f - R_o}{j\omega L_o}$$

$$= \frac{L_f}{L_o}\left[1 - j\cdot\left(\frac{R_f - R_o}{\omega L_f}\right)\right] \tag{29}$$

From (21) and (29) the effect of core losses on head sensitivity is

$$\frac{\sigma_f}{\sigma_o} = \frac{L_f}{L_o}\left(1 - j\cdot\frac{R_f - R_o}{\omega L_f}\right)$$

or

$$\left.\begin{aligned} \left|\frac{\sigma_f}{\sigma_o}\right| &= \frac{L_f}{L_o}\left(1 + \frac{1}{Q_f^2}\right)^{\frac{1}{2}} \\ \tan\phi &= \frac{1}{Q_f} \\ Q_f &= \frac{\omega L_f}{R_f - R_o} \end{aligned}\right\} \tag{30}$$

where

5.3. Core Materials and Methods of Construction.

5.3.1. Losses in Laminated Alloy Cores.

The most frequently used core materials, particularly in the lower-frequency ranges, are nickel-iron alloys. These materials have an extremely high permeability but comparatively low resistivity so that normally they must be laminated if excessive eddy-current losses are to be avoided. For a lamination thickness δ and resistivity r the eddy-current loss gives rise to a complex permeability of real and imaginary parts[19],

$$\mu' = \frac{\mu_o}{\psi}\cdot\frac{\sinh\psi + \sin\psi}{\cosh\psi + \cos\psi}$$

$$\mu'' = \frac{\mu_o}{\psi}\cdot\frac{\sinh\psi - \sin\psi}{\cosh\psi + \cos\psi} \tag{31}$$

where

$$\psi = 2\pi\delta\sqrt{\frac{\mu_o f}{\rho}}$$

In most cases the eddy-current loss will be much greater than the hysteresis or residual loss, even when considering recording or erasing heads in which the maximum flux density may be quite high. Equations (31) may, therefore, be used in conjunction with (25) to give a close estimation of the head sensitivity loss using a laminated material of known properties. For values of $\psi > 5$, $\sinh\psi \approx \cosh\psi$ and both are much greater than unit. Then from (31)

$$\mu' \approx \mu'' \approx \frac{\mu_o}{\psi}$$

and (25) becomes

$$\frac{\sigma_f}{\sigma_o} = \frac{\sqrt{2}(\gamma\mu_o + 1)}{[(\gamma\mu_o + \psi)^2 + (\gamma\mu_o)^2]^{\frac{1}{2}}} \tag{32}$$

Thus when $\psi \gg \gamma\mu_o$, the sensitivity of a laminated head will tend to fall at a rate proportional to the square root of frequency and the phase lag in this range will tend towards 45°.

As an indication of the lamination thickness required consider a possible head in which the front gap is 0·3 mil, the core is 1·5 inches in length and the halves of the core are interleaved to avoid a rear gap. Let the laminations be of such a material that r = 40 microhms/cm³ and let μ_o = 10 000 so that $\gamma\mu_o = 2$. If the application is such than an eddy-current loss of 6 dB is acceptable at 16 kc/s then the thickness of lamination must not exceed 6 mil. For the same loss at 600 kc/s the lamination thickness must not exceed 1 mil.

In practice, for lamination thickness below 5 mil, the improvement obtained will seldom be as great as that expected from simple theory. Additional losses, possibly due to surface skin effects, become significant and the laminations are difficult to prepare. Also, mechanical working after the final heat treatment, a certain amount of which is usually unavoidable in head manufacture, may cause large local reduction in the effective permeability when dealing with very thin laminations.

5.3.2. Losses in Ferrite Cores.

Eddy current losses can be reduced to negligible proportions by making head cores of ferrite material, the resistivity of ferrites being a million or more times that of the commonly used alloys. In these materials, residual loss is the important factor at low inductions and a combination of residual and hysteresis loss at high inductions. Several types are commercially available covering a wide range of permeability, residual loss coefficient, maximum flux density, and coercivity. In general the permeabilities and maximum flux densities are much lower, and the coercivities much higher, than those of magnetic alloys.

In the case of reproducing heads, the desirable properties are high permeability and small residual loss. The information supplied by manufacturers of ferrites usually includes curves showing the variation of the components of the complex permeability with frequency. If such curves are available the most suitable material for a particular reproducing head application can be chosen by calculating sensitivity-frequency curves from (25) and deciding which curve has the highest sensitivity over the required frequency range. Usually it will be found, however, that ferrites of permeability much less than 1000, even though they may have very small losses, give an unacceptably poor sensitivity at low frequencies so that the number of ferrite grades to choose from is really very small. Using available ferrites of permeabilities of the order of 1000 it is, nevertheless, possible to design a reproducing head with negligible loss up to a frequency of approximately 1 Mc/s. However, depending upon the gaplength requirements and the degree to which the pole-tips can be tapered towards the gap, the sensitivity of the ferrite head will probably be appreciably poorer than that of a laminated alloy head at the lower frequencies.

In choosing the core for a recording head it is again desirable that the ferrite should have high permeability and low residual loss. Other factors must however, be taken into account, particularly when a high value of h.f. bias current is envisaged. Even without bias, the flux density in the core created by the signal current may be high enough for hysteresis losses to become appreciable at the higher frequencies, and a ferrite of low coercivity should be used. In the case of erasing heads and heavily-biased recording heads, hysteresis effects may cause excessive losses which, since ferrites are usually poor thermal conductors, may give rise to overheating. In extreme cases when out-of-contact working, or high-coercivity tape necessitate very high bias and erase currents, the temperature of the core may rise above the Curie point which is of the order of 150°C for ferrites. It may also be found, in applications of this kind, that the maximum flux density of certain grades of ferrite is prohibitively low.

5.3.3. Construction of Ferrite Cores.

Attention was confined in the preceding section to considering the potentialities of ferrite cores in so far as they are a means of reducing core losses. Their use, however, introduces new problems of construction and finish, some of which are very difficult of solution. Three principal difficulties arise:

(a) Ferrites are difficult to mould in small intricate shapes owing to their severe contraction after sintering.

(b) They are brittle and cannot be easily worked except by grinding.

(c) The surface finish obtainable appears to be limited owing to the existence of small holes and fissures throughout the material and the ease with which splintering occurs during polishing.

The first two difficulties can be largely overcome by developing suitable grinding techniques. The third is more difficult to surmount and attempts made so far have not met with a great deal of success. It is, indeed, possible to polish the relevant faces of the halves of a ferrite core, assemble them with a suitable gap spacer, polish the front surface, and obtain a finish which looks satisfactory under the microscope. When the head is put into service, however, it is inevitably found that the performance rapidly deteriorates; tape dust piles up on the contact surface and, when cleaned and re-examined under the microscope, the finish is found to be poor. These findings have been confirmed by other workers[20].

Until such time as a more suitable ferrite material is developed, a method[21] of overcoming this difficulty, and which can, with care, be made to give quite satisfactory results, consists of facing a ferrite core with a thin sheet of high-permeability alloy. The technique is essentially one of combining the good surface-finish and wearing properties of the alloy with the low core losses of the ferrite. The alloy is cemented to the two halves of the core before the gap faces are polished and the head then assembled. The alloy sheet should, of course, be as thin as possible to avoid eddy-current effects and the gap between it and the core proper should be as small as possible to avoid excessive loss in general sensitivity. An advantage of the technique is that, by sharply tapering the ferrite pole tips below the alloy face and by using an alloy of permeability much greater than that of the ferrite, an effective value of γ can be obtained which is considerably greater than b/l.

6. SOME PROBLEMS IN THE DESIGN OF ASSOCIATED ELECTRICAL EQUIPMENT.

6.1. Reproducing Head Transformer Requirements.

With perhaps some minor exceptions, confined to low-frequency systems, it is not practicable to wind a reproducing head with enough turns to feed it directly into the grid of the amplifier, and a transformer is required. The design of the head winding is then not critical but it should be such as to avoid an unduly low Q factor at the extremes of the frequency range. Assuming a comparatively loss-free transformer core, the input winding is decided primarily in relation to the d.c. resistance of the head. The secondary winding, on the other hand, is limited to the point where the transformed impedance of the head (largely inductive) becomes comparable with the reactance of the combined shunt capacities of the secondary winding and the amplifier input stage.

In comparatively low-frequency systems, a large secondary inductance, and hence a high step-up ratio, can be tolerated and the signal applied to the grid is large enough for tape noise, rather than amplifier noise, to be the factor limiting signal/noise ratio. In systems going to high frequencies, however, this may no longer be the case. It will have been apparent from the section on core losses that, generally speaking, the greater the bandwidth to be accommodated the lower the sensitivity of the head. This situation is further aggravated by the fact that the permissible turns-ratio of the reproducing transformer decreases with increasing bandwidth. In fact, if the total capacity shunted across the transformer secondary remained constant, the possible turns-ratio would be inversely proportional to the highest frequency to be transmitted. In practice, the limitation will not be quite so severe since the self-capacity of the winding will tend to decrease as the turns are reduced.

6.2. Equalisation of Response.

In general, the overall response (E/I) of a magnetic recorder at first rises, at a rate approximately proportional to frequency, to a maximum and then falls with increasing frequency owing to the combined effect of the various losses detailed in previous sections. Let it be assumed that the inherent differentiation of the system has been corrected by inserting a suitable integrating stage into the reproducing amplifier. The amplitude-frequency characteristic is then (ignoring very long-wavelength losses) essentially that of a low-pass network which can be corrected by inserting the appropriate high-pass network in the chain. How much of the amplitude correcting circuit is placed in the recording amplifier and how much in the reproducing amplifier depends upon a variety of factors, such as the average spectrum of the signal and the noise and distortion characteristics of the particular system considered. Ignoring this aspect of the problem, however, amplitude equalisation is a straightforward matter and can be continued up to the point when either the signal/noise ratio becomes inadequate or further equalisation would be valueless due to intolerable amplitude modulation of the signal at still higher frequencies.

Equalisation of the phase as well as the amplitude characteristic of the magnetic recording system may be more difficult, however, depending on the nature of the losses. In so far as the amplitude and phase relationships of these losses are approximately similar to those which occur in linear, passive, electrical networks

then, theoretically at any rate, their correction is a straightforward matter. Core losses in the heads, which fall into this category, can, for example, be corrected in phase and amplitude by comparatively simple methods. Thus if laminated heads are used in which eddy currents cause the major loss, the combined loss is eventually proportional to frequency and causes an eventual phase lag of 90°. Fundamentally, therefore, these losses can be corrected by means of a simple R.C. network. Another technique, applicable in simple form to recording head core losses, would be to apply a negative feed-back voltage to the input of the recording amplifier derived from the integrated e.m.f. from a secondary winding on the head. If sufficient gain can be inserted in the feedback loop, a linear relation between head flux and current can be obtained regardless of core losses. A similar, though somewhat more complicated, procedure may be used to correct losses in a reproducing head if so desired.

The various other losses in the system do not, however, have a parallel in linear passive networks. Thus the aperture effects are purely amplitude losses which introduce no distortion of phase unless the response actually contains a reproducing-gap minimum, or recording-gap interference effects are present. Similarly the separation loss (Section 3.1.4) and the tape thickness loss (Section 3.2.1) also represent attenuations which increase with decreasing wavelength without any associated phase change. Ideally, therefore, all these losses may conveniently be equalised using derivative equaliser techniques[22], in which only even-power derivatives of frequency f, (where $f = v/\lambda$ and v is the tape velocity) are involved. In practice the degree to which the equalisation curve required may be approximated is limited by the highest power derivative which may be made available from the equaliser with an acceptable signal-to-noise ratio. The derivative equaliser method has the advantage that adjustments can be made while the system is actually operating and, by introducing odd-order derivatives (the first is usually to hand in the form of the direct output from the reproducing head) as well, correction can be made at the same time for the losses that occur in the head cores and in the associated electrical equipment. Alternatively the synthesis of the equalisation circuits can be carried out by first correcting the system response for amplitude and then correcting the amplitude-correcting networks for the phase distortion they will have introduced. However, it is not easy to carry out phase measurements on recording equipment, owing to the fact that there is a large (indefinitely large on separate record and replay) delay between output and input and, inevitably, a certain amount of wow and flutter. The only possible techniques are similar to those used in making measurements on long lines or radio links when the input signal is not available for comparison with the output.

6.3. Frequency of Bias and Erase Supplies.

It has been noted that, in the ordinary way, a requirement of good linearity can be met in magnetic recording equipment only by means of h.f. biasing. In many cases, however, its use may impose certain limitations on the highest signal frequency that can be accommodated by the system. In addition to the "over-biasing" effect at short wavelengths the use of bias may cause further difficulty in that the recording head must, in effect, be designed to handle a considerable amount of power at a frequency normally many times greater than the highest signal frequency. Thus, if overheating or other considerations limit the highest bias frequency to a value f_b, the highest signal frequency that can be satisfactorily biased is automatically limited to a value f_b/K where K ought to be at least three and preferably greater. With smaller values of K the biasing action becomes less efficient and the signal level

falls. In addition, unwanted frequency components may be generated within the signal bandwidth owing to interaction between signal and bias if the frequency and amplitude of the latter is too low to provide adequate linearity.

The situation regarding the choice of the frequency of the erasing head current is less critical. It should be remembered, however, that a tape will be in a completely demagnetised condition after leaving an erasing head only if the frequency of erasure is, in effect, well above the highest signal frequency that could be recorded if the erasing head were used as a recording head (without, of course, using bias). In practice, this condition is usually fulfilled if the frequency of erasure is only slightly in excess of the highest signal frequency and, in any event, the presence of a small recorded "erasing signal" will generally be masked by the action of the bias during recording.

7. SPECIAL SYSTEMS.

7.1. Modulated Carrier Systems.

The fundamentally low output of the conventional reproducing head at very low frequencies, and its inefficiency in collecting flux at the long wavelengths with which low frequencies are usually associated, may be overcome by modulating a suitable carrier with the signal it is desired to record and arranging for the modulated carrier to be recorded on the tape. On reproduction the carrier is demodulated by appropriate means and the original modulating signal made available. Any of the known systems of amplitude or frequency modulation or any of the forms of pulse modulation may, in principle, be adopted, the choice depending on the nature of the modulating signal and the high-frequency and other properties of the recording system. In each case design features such as the magnetic heads and the tape speed must be chosen so that the highest frequency present can be adequately recorded and reproduced. The tape speed necessary will be many times that required to record the highest modulating frequency conventionally so that all carrier systems are uneconomic in the use of tape and they are employed only when some over-riding advantage is to be obtained. If amplitude modulation is employed the effect of the unwanted amplitude modulations which arise from the particular nature of the tape may be enhanced in so far as these fluctuations increase in magnitude at the shorter wavelengths associated with the carrier and its sidebands. If frequency modulation is employed the advantage of freedom from noise or other unwanted amplitude fluctuations is obtained but stringent requirements are imposed on the performance of the system in regard to speed constancy. If the speed constancy is not adequate the effects of wow, flutter, or longitudinal vibrations along the tape, which themselves create frequency modulation, will appear in the final output and may offset advantages due to the elimination of other unwanted amplitude modulations.

In considering the use of carrier modulation to overcome low-frequency difficulties, it must be remembered that, physically, the efficiency of the conventional recording process is unimpaired at low frequencies and that it is the properties of the reproducing head which demand the change of technique. It is not always necessary to adopt a carrier method to overcome low-frequency difficulties and in the next section an alternative type of reproducing system will be described which has higher efficiency in this region and allows the recording chain, and the tape speed, to remain unchanged.

Another property of conventional recording which may, at times, be troublesome and which can also be avoided by the carrier technique, is the accidental printing which occurs between the layers of a recorded tape when it is wound up into a reel. In the reel the coating layers are separated from one another by a distance of the order of the backing thickness and each layer is subjected to static magnetic fields emanating from adjacent recorded layers. The permanent magnetisation which can result under favourable conditions, although small, may be of such a magnitude as to give audible echo effects on subsequent reproduction, or, at least, contribute to the general background noise. The level of accidental printing depends, amongst other factors, on the recorded wavelength[23], a maximum transfer being obtained when the condition $\lambda = 2\pi d$ is fulfilled, where d is the separation between the magnetic layers and λ is the recorded wavelength. As the wavelength decreases below this value the level of accidental printing decreases rapidly. Thus all carrier systems are inherently more free than conventional systems from the effects of accidental printing in that the wavelengths on the tape are all short and $\lambda \ll 2\pi d$. The frequency modulation carrier system has an added protection in that the effects of any amplitude fluctuation noise of this type may be eliminated by suitable limiting in the demodulation process.

7.2. Flux-Sensitive Reproducing Systems.

Systems required to operate down to very low frequencies, but which are not required to transmit d.c. signals, need not necessarily be of the modulated carrier type. Instead, the inherent decrease in efficiency of the conventional reproducing head at low frequencies can be avoided by substituting for it a so-called "flux-sensitive" reproducing head. Essentially this has the same form as a normal head, but the simple coil is replaced by a pick-up device such that the output is proportional to the actual magnitude of the core flux, rather than to the rate of change of this flux with time. In this way the output level, subject to the fundamental limitations imposed when the recorded wavelength becomes comparable with pole-piece dimensions, is fundamentally independent of signal frequency. The level of output is also, with no reservations, independent of the tape speed on reproduction and this type of head can, if desired, be used to make tape flux measurements along the length of a stationary tape.

Several types of flux-sensitive reproducing head have been described[24,25]. In one type, the head flux is made to deflect an electron beam so that the voltage produced between two plates on which the beam impinges is a measure of the flux. The others depend essentially upon some kind of second-harmonic modulator principle, in which the output is obtained by demodulating the second harmonic of a high-frequency excitation flux generated in the core.

Compared with modulated carrier techniques the flux-sensitive head principle is more economical in that the tape used need only be sufficient to accommodate the highest signal frequency. In general, however, the signal/noise ratio is rather poorer.

7.3. Multi-track Systems.

In some applications of magnetic recording information from several sources is required to be recorded simultaneously and this has led to the development of

multi-track systems in which the various input signals are handled by separate pairs of recording and reproducing heads on adjacent tracks on the recording medium. Such requirements arise, for example, in stereophonic recording, telemetering recording and computor stores. Two-track recorders are, of course, fairly common but in most cases the two recording heads cannot be energised simultaneously and the two reproducing heads cannot reproduce simultaneously, the two tracks being provided only as a method of greater utilisation of the standard ¼ in. tape. Where simultaneous recording or reproduction of two or more tracks is required the situation becomes more complicated, especially when some specific time or phase relationship of the various input signals must be preserved with the minimum error. In this case the distance between each pair of associated recording and reproducing heads must be the same (to within the accuracy required) and problems of cross-talk must be considered. One procedure which has been adopted is to "stagger" the recording and the reproducing heads in an echelon formation across the width of the tape or drum so that each head may be individually manufactured and adjusted in position. This procedure has various advantages in that direct cross-talk between the various heads is eliminated and the alignment of each reproducing head may be adjusted to match its associated recording head. Difficulties arise, however, when great time or phase accuracy is required between the various reproduced signals and complicated mechanical adjustments may have to be provided to make the various head spacings equal and maintain them so under conditions of mechanical movement or temperature change. An alternative method which avoids difficulties of the latter type is to manufacture the heads in a composite stack and ensure, by a suitable manufacturing process, that all the gaps are in perfect alignment both with respect to one another and with respect to the direction of tape travel. The difficulties are then transferred to the manufacturing process and these are obviously greater as the number of heads in the stack is increased and as the permissible time or phase error is decreased. In one method of manufacture which has been described[26] each stack of heads is manufactured in two halves with respect to a centre-line through the centre of the gaps. It is, of course, necessary to insert magnetic screens between the magnetic heads in recording and reproducing stacks in order that cross-talk is kept to a reasonable level and this requirement only increases the manufacturing difficulties. The magnetic screens which lie between each pair of heads and prevent direct cross-talk from one head to another do not reduce very much the inter-track cross-talk which arises at long wavelengths when flux from one track may spread into the recording head of an adjacent track. This type of cross-talk will, of course, be present in both stack and echelon systems. If the cross-talk so arising cannot be tolerated then the track separation must be increased or a carrier system adopted in which the order of recorded wavelengths is shorter and the spread of flux correspondingly less. An interesting situation, which illustrates cross-talk difficulties, as well as the low-frequency difficulties discussed earlier, has been reported by Olsen and his collaborators[27] in describing a television recording system in which the video and associated audio signals were recorded on adjacent tracks on a magnetic tape. A high tape speed of 360 in./sec was required to record the high-frequency content of the video signal so that the wavelengths of the lower audio frequencies were exceptionally long when conventionally recorded. The signal-to-noise ratio in the audio channel was found to be unacceptable under these conditions and the cross-talk into the video channel, due to the spread of flux from the audio track, was found to be serious. An amplitude modulated carrier system was, therefore, adopted for the recording of the audio-frequency signal.

8. CONCLUSION.

From the discussion and analysis in the body of the paper it is possible to set down some improved characteristics which are desirable in the elements of the magnetic recording system if the present limits of usefulness are to be extended. Some difficulties, such as the low-frequency inefficiency and the long-wavelength losses which occur in a conventional reproducing head (Section 3.1) are, of course, fundamental and can only be overcome by a change of recording or reproducing technique. However, the new technique may involve the designer in a new range of difficulties of a different, but not necessarily more tractable, kind. Thus, the low-frequency and long-wavelength difficulties can, in principle, be overcome by the use of a carrier system but if the low frequencies are only part of a wideband signal this technique may present formidable high-frequency and/or short-wavelength difficulties. Similarly, unwanted amplitude modulations occurring in the recording system may be overcome by the use of a frequency-modulated carrier method but special attention must then be paid to the speed constancy of the recording system. Similar obstacles must be overcome if really high frequencies or really wide bandwidths are to be directly recorded without recourse to excessive circuit complications and high tape speeds. In general it appears that the most fruitful advance towards the greater utilisation of magnetic recording is an improvement of the high-frequency and short-wavelength performance of the system. Here again it must be emphasised that a lowering of the noise level in these regions is as valuable as an increase of signal level. The developments required are partly of a magnetic and partly of a mechanical nature and these two categories may be said to affect the high-frequency and short-wavelength performance respectively. The requirements may be summarised under three headings as follows:

(a) The Heads
(b) The Tape
(c) The Tape Transport System.

8.1. The Heads.

The developments required to make the heads operate more effectively are in core material. The laminated Mumetal cores employed in audio-frequency applications are unsuitable for the higher range of frequencies which it is now required to record owing to the severe eddy-current losses which occur there. Although the ferrite cores available (and for which there is, at present, no alternative) are better than Mumetal cores in this respect, they are inferior in most other respects. Firstly, lower hysteresis and residual losses are desirable to maintain the signal strength at high frequencies. Moreover, the heat generated by these losses is especially inconvenient at the high flux-densities and high frequencies necessary for bias and erase fields for the extreme precision necessary in the construction of the modern wide-range head allows little heat to be present without the possibility of serious damage due to the mechanical distortion. Secondly, the cores should possess much better machining properties to allow the accurate manufacture of the fine gaps and intimate contact surfaces which are now necessary. The finish when obtained should be highly stable in contact with the moving tape to obviate the necessity of Mumetal or other facings.

8.2. The Tape.

The magnetic properties of the coating should be such that a high maximum sensitivity is obtainable at a low value of bias field. The output/bias characteristic

should not reveal too sharp a maximum at this point to avoid extreme changes of recorded intensity as a result of small changes of separation between the recording head and the tape. For short-wavelength applications the various magnetic components of the coating should require similar critical fields (h_c) to provide permanent magnetisation (Section 3.2.4). The smaller the range of critical fields required the less marked will be the trailing edge 'aperture' effect. Considering mechanical improvements the coating should possess a higher uniformity of distribution and a surface smoothness which allows great intimacy of contact with the heads. The effective separation from the heads will then be small, so that good short-wavelength performance is obtained, and the basic modulation noise of the system will be low. The mechanical properties of the backing are almost equally important and it should be flexible, free from appreciable stretch and stable under normal variations of temperature and humidity. The surface of the backing should also be smooth to avoid the introduction of random changes in the coating distribution near the base. In manufacture the width of the tape should be maintained within the closest tolerances so that the guiding system may be manufactured to the high accuracy required to eliminate appreciable alignment errors.

8.3. The Tape Transport System.

The tape transport system should introduce no unwanted frequency or amplitude modulation of the signal to be stored. The reduction of frequency modulation (wow and flutter) is mainly a matter of careful design and manufacture of the mechanical system. Thus all rotating surfaces which can affect the speed of the tape should be most carefully machined and fitted and careful attention paid to the design of mechanical filters which will reduce any residual errors. Longitudinal oscillations of the type described in Section 4.4.2 are extremely important as higher tape speeds and shorter wavelengths are employed and the surfaces of the guides and of the heads must be carefully polished, to reduce friction to a minimum, and loading pulleys must be placed at suitable points between the heads. Amplitude, as well as frequency, modulation is contributed by the transport system when variations in tape tension occur. These may arise from changes in the surface friction of the tape over the heads or in the guides from width variations along the tape, from inaccurate spooling and from spooling motors with unsuitable characteristics. All these errors may be reduced to a low incidence by suitable attention to design, manufacture and adjustment.

9. REFERENCES.

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